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FIRE SAFETY TESTS COMPARING SYNTHETIC JET AND DIESEL FUELS WITH JP-8

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Fire safety tests comparing synthetic jet and diesel fuels with JP-8

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ABSTRACT

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1. Introduction

The United States Air Force has used petroleum-derived kerosene fuels for its turbine engines since the 1940s. JP-8 (jet propellant 8) has been in use since the 1980s because it has a lower volatility than previously used fuels (e.g., JP-4), which provides increased safety for the aircraft [1]. Due to the energy demands for petroleum and to provide increased energy independence to the United States, the Air Force has begun necessary steps to replace a portion of the petroleum demand with alternative (synthetic) sources. In this effort, the Air Force has performed engine, ground, and flight tests for various aircraft. In particular, successful flight tests were performed in all eight engines of a B-52 using a 50/50 blend (by volume) of JP-8 and synthetic jet fuel derived from a Fischer–Tropsch process. A cross country flight of a C-17 and supersonic flights of a B-1 and an F-15 were also performed using a 50/50 fuel blend. Also, aerial refueling with a 50/50 fuel blend was performed on an F-22.

With the increase of alternative fuels usage in aircraft, fire safety issues regarding these fuels need to be addressed. The military typically uses a fire fighting agent, aqueous film-forming foam (AFFF), to extinguish liquid fuel fires [2]. MIL-F-24385F (mil-spec) is an AFFF procurement specification produced by the military that gives chemical and physical properties required for the agent. Part of this document includes requirements of extinguishment and burnback time for experimental test fires using AFFF on unleaded gasoline. The test fire standards outlined in the mil-spec are more challenging than other known extinguishment standards [3]. The National Fire Protection Association incorporated the 50 ft² (4.6 m²) mil-spec fire test into their own standard [4] that allows for use of any foam agent. The procedures used in the mil-spec fire tests were applied to the experiments using fuels from conventional (petroleum) and alternative (synthetic) sources, comparing the extinguishment and burnback characteristics to those of the Air Force's JP-8 fuel.

2. Fuels background

Fire tests were performed on commercially available fuels that were divided into two categories: kerosene and diesel fuels. The kerosene fuels consisted of the conventional jet fuel provided by Shell (JP-8) and two synthetic fuels (synthetic paraffinic kerosene (SPK)) produced by Syntroleum Corporation (S-8) and Shell (Fischer–Tropsch isoparaffinic kerosene (FT-IPK)). The diesel fuels consisted of Shell's conventional diesel fuel (2-D) derived from petroleum and Syntroleum's synthetic diesel fuel (S-2). Also, 50/50

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mixtures (by volume) of conventional (e.g. JP-8) and synthetic kerosene were used in fire experiments. Since JP-8 is the current fuel used by the U.S. Air Force, it was used as a baseline to which all other fuels (both kerosene and diesel) were compared.

Conventional kerosene is obtained by fractional distillation of crude oil at temperatures between 150 and 275 °C, which typically has mixtures of mostly aliphatic hydrocarbons ranging from C₈ to C₁₆. Further processing yields the commercially available jet fuel (A or A-1) with an average molecular formula C₁₁H₂₁, being about 25% aromatics and 75% saturated (paraffin and naphthene) hydrocarbons [5]. JP-8 is produced from jet fuel A by adding a corrosion inhibitor/lubricity improver, an anti-static additive, and a fuel system icing inhibitor [6]. S-8 and FT-IPK fuels are both obtained by steam reforming of natural gas, followed by a Fischer–Tropsch process using a low-temperature cobalt catalyst to obtain > 99% saturated (mainly n- or iso-paraffin) hydrocarbons with S-8 ranging from C₇ to C₁₈ (average C₁₂) and FT-IPK ranging from C₈ to C₁₃ (average C₁₀) [7].

Conventional diesel is also obtained by fraction distillation of crude oil, but at temperatures higher than kerosene between 200 and 350 °C. 2-D diesel fuel typically contains more aromatics than kerosene at 35% as well as a higher average molecular formula C₁₂H₂₆ [5]. Similar to the SPK fuels, the synthetic S-2 fuel is also produced by reforming natural gas followed by a Fischer–Tropsch process, but different refining is used to obtain the desired fuel composition with an average molecular weight of C₁₂H₂₆ and > 99% saturated hydrocarbons [8], quite different than the 35% aromatics in conventional diesel fuel.

Studies of the physical properties have been previously performed on these fuels, and comparative analyses were performed

on each fuel category (e.g., kerosene fuels [7] and diesel fuels [8]) by following the military specification for jet fuel [9]. Some of these physical properties pertinent to combustion and flame spread are presented in Table 1. Not all test methods in Table 1 were performed at the same location, nor were the same methods used to determine the same physical parameter; thus some variation was observed. Moses [7] found that the physical properties varied substantially between batch samples, though all specifications [9] for the SPK fuels were met except for density, which was below the specified range. Despite the variation in the data, Table 1 presents a reasonable estimate of the properties of the various fuels, though no specific fuel data were used for the analysis of this work.

3. Experimental methods

The fire suppression experiments followed the outline given by the mil-spec [2], which provides the parameters for using AFFF for extinguishing pool fires of unleaded gasoline. These experiments were performed in an indoor facility (88 × 80 × 32 ft³ [27 × 25 × 10 m³]) with quiescent air, allowing for repeatable and stable conditions between fire tests. The test apparatus consisted of a stainless steel 6 ft (1.83 m) diameter pan with a height of 4 in. (10.2 cm). To help protect the pan, the pan was filled with a shallow layer (0.25–0.5 in. [0.6–1.3 cm]) of water. Approximately 10 gal (37.9 L) or 0.57 in. (1.44 cm) of the desired fuel was then added. All mil-spec tests for each fuel type used came from the same batch, thus limiting variation seen between different batches of fuels [7]. The amount of fuel was not a limiting factor in performing all aspects of the mil-spec burn test, i.e., 10 gal (37.9 L) was sufficient

Table 1
Physical properties for fuels used in fire suppression experiments.

Property	SPK test method	S-8	FT-IPK	JP-8		JP-8/ S-8		JP-8/ FT-IPK	Diesel test method	S-2	D-2
				Edwards	Dyess	Edwards	Dyess				
Composition											
Aromatics (volume %)	ASTM D – 1319	0	0.2	16.5	19.1	8.3	8.7	ASTM D – 1319	ND		30
Olefins (volume %)	NA	NA	NA	NA	NA	NA	NA	ASTM D – 1319	ND		1
Saturates (volume %)	NA	NA	NA	NA	NA	NA	NA	ASTM D – 1319	> 99		69
Total sulfur (mass %)	ASTM D – 4294/2622 ^a	0.002	< 0.01	0.06	0.09	0.029	0.05	ASTM D – 2622	ND		0.05
Hydrogen content (mass %)	ASTM D – 3701/3343 ^a	15.4	NA	13.8	13.7	14.5	14.6	NA	NA		NA
Particulate matter (mass %)	ASTM D – 2276-5452 ^a	0.00013	NA	NA	NA	NA	NA	ASTM D – 482	< 0.001		0.01
Volatility											
Initial boiling point (°C)	ASTM D – 86	144	154.1	145	182	148	160	ASTM D – 86	160		184
10% recovered (°C)	ASTM D – 86	167	160.8	172	196	170	171	ASTM D – 86	199		216
20% recovered (°C)	ASTM D – 86	177	162.3	181	200	179	175	NA	NA		NA
50% recovered (°C)	ASTM D – 86	206	168.0	205	209	206	188	ASTM D – 86	256		258
90% recovered (°C)	ASTM D – 86	256	183.3	252	224	253	216	ASTM D – 86	316		310
Final boiling point (°C)	ASTM D – 86	275	195.2	277	244	275	236	ASTM D – 86	350		341
Residue (%)	ASTM D – 86	1.5	1.0	1.3	1.1	1.3	1.0	NA	NA		NA
Loss (%)	ASTM D – 86	0.9	1.0	1.3	0.6	1.1	0.3	NA	NA		NA
Flash point (°C)	ASTM D – 56/93/3828 ^a	45	43	48	64	48	50	ASTM D – 93	64		69
Other tests											
Density (kg/m³)	ASTM D – 4052	756	736	807	808	782	773	ASTM D – 1298	770		845
Freezing point (°C)	ASTM – 2386/5972 ^a	-51	-53.8	-52	-52	-52	-61	NA	NA		NA
Viscosity (cSt)	ASTM D – 445 ^b	4.9	2.49	4.8	4.9	4.6	3.6	ASTM D – 445 ^c	2.1		2.5
Net heat of combustion (MJ/kg) ^d	ASTM D – 3338/4809/4529 ^a	43.9	44.2	43.2	43.1	43.4	43.5	ASTM D – 240	42.4		NA
Lubricity (mm)	ASTM D – 5001	0.58	0.92	0.56	0.53	0.54	0.54	ASTM D – 6079	< 0.37		NA
Acidity (mg KOH/g)	ASTM D – 3242	0.004	0.003	0.004	0.004	0.005	0.003	NA	NA		NA

SPK fuels taken from Moses [7], diesel fuels taken from Woodward [8], Edwards and Dyess are U.S. Air Force bases where the tests were performed (see [7] and [8]). NA, not available; ND, not detectable.

^a Test methods varied between fuels or multiple tests were performed and an average was given.

^b At –20 °C.

^c At 40 °C.

^d High heating value.

for the fuel to ignite, extinguish, and allow for burnback without affecting the times of extinguishment or burnback. The pan, water, and fuel were all at the same room temperature ranging from 16 to 24 °C depending on facility conditions at the time of the experiment.

The fuel near the perimeter of the pan was ignited with a propane torch, and the flames were allowed to propagate towards the center, creating a fully developed (steady-state) fire plume. The mil-spec for unleaded fuel specified that the flame burns freely for 10 s (preburn time [t_{pb}]). Since unleaded gasoline has a flash point of -40 °C, a 10 s preburn time is sufficient for a fire plume to become fully developed. However, the flames from kerosene fuels with higher flash points (37–62 °C) propagated more slowly than gasoline; thus additional preburn time was required for a fully developed plume, with values ranging from 17 to 32 s among the various fuel configurations, the average being about 23 s for all fuels. A test manager (same for all tests) visually determined the preburn time (when the flames were fully developed and had a consistent flame height of approximately 15 ft [4.5 m] and were pulsating), time of extinguishment, and time of burnback. Video recordings from cameras positioned at eye level and from above verified the extinguishment (uncertainty ± 0.5 s) and burnback (uncertainty ± 4 s) times determined by the test manager.

After the initial preburn time, the fire was attacked with a 10 gal (37.9 L) fire extinguisher filled with 3% (by volume) Chemguard AFFF-MS (C301MS, Military Specification AFFF Foam Concentrate, QPL listed) and water (0.3 gal AFFF and 9.7 gal water). The agent was delivered to the flames by a 2 gal/min (0.13 L/s) nozzle (according to mil-spec) at a pressure of 100 psi (6.9 bar); the flow rate was verified after every two test runs, while the pressure was checked before every run to ensure consistency. The fire was “attacked and extinguished as expeditiously as possible” [2], and the time of extinguishment (t_{ex}) was determined by the test manager. The firefighter initially applied AFFF from a fixed position of approximately 3 ft (1 m) from the perimeter of the pool fire so that the foam landed in the middle to back-side of the fuel pan. After approximately 12 s, the firefighter moved to the opposite side of the pan and applied foam to any sections of the pan to quickly extinguish the fire. The mil-spec standard indicates that t_{ex} should be less than 30 s when using gasoline. Agent application continued for a total of 90 s or approximately 3 gal (11.4 L) of agent.

Within 60 s of the end of agent application, a steel 1 ft (0.305 m) diameter (burnback) pan filled with 1 gal (3.79 L) of flaming fuel was positioned by the firefighter using a metal rod in the center of the foam-applied 6 ft diameter (agent) pan, beginning the burnback portion of the mil-spec test. Unleaded gasoline [2] was used as the burnback (flaming) fuel regardless of the fuel being tested in the agent pan. The foam near the burnback pan gradually disintegrated/pyrolyzed, allowing for the fuel in the agent pan to reignite and spread anew. Once this occurred the burnback pan was removed from the agent pan. The flames in the agent pan were allowed to break up the foam blanket and propagate until the flames covered approximately 25% of the agent pan area. This burnback time (t_{bb}) was determined by the test manager. The mil-spec standard indicates that t_{bb} should be greater than 360 s when gasoline is used. It has been found that this 25% area is a threshold where radiation begins to dominate, due to a larger surface area pool fire, and becomes turbulent. After this threshold, the remaining foam disintegrates relatively quickly (1 min compared to 10 min burnback) and the pool becomes fully developed again.

The firefighter (same for all tests) who performed these experiments was DOD-certified and experienced with the specific requirements and techniques used for the mil-spec tests. A limited amount of S-2 diesel fuel was available for the mil-spec tests; hence, only two experiments were performed. For the mil-spec tests, the average t_{ex} and t_{bb} for each fuel or 50/50 mixture was compared to those of the baseline JP-8 using t -tests. The

hypotheses tested were that the time to extinguish (t_{ex}) the synthetic fuels and the burnback time (t_{bb}) of the synthetic fuels were no different than the times for JP-8. If the probability resulting from the t -test was less than 5%, the comparison was statistically significant. If the probability values were greater than 5%, no statistical difference in the times could be determined from the sample sets.

4. Calculations

Heat transferred to the pan/pool from the flame could make a significant difference in reducing the drainage time of AFFF. To demonstrate this, a simple energy balance was performed showing the combustion process of the pool fire. The combustion was plume modeled to be a cylinder with height L_f that is broken into two radiative sections (see Fig. 2), the upper (u) section where no effective radiation can heat the pan due to soot obscuration and the lower (l) section where a part of the radiation can heat the pan (e.g., Fig. 1). The separation distance between sections is defined by a visible flame fraction (F_f) multiplied by L_f :

$$\dot{Q}_{comb}'' = \dot{Q}_{rad,surr}'' + \dot{Q}_{rad,pool}'' + \dot{Q}_{ent}'' \quad (1)$$

The combustion process provides heat for the steady-state system, whereas air entrainment and radiation to both the surrounding and the pool remove heat from the system (Eq. (1)).



Fig. 1. Comparison of smoke properties for JP-8, SPK (S-8), and SPK/JP-8 blend including estimates of flame fraction (F_f).

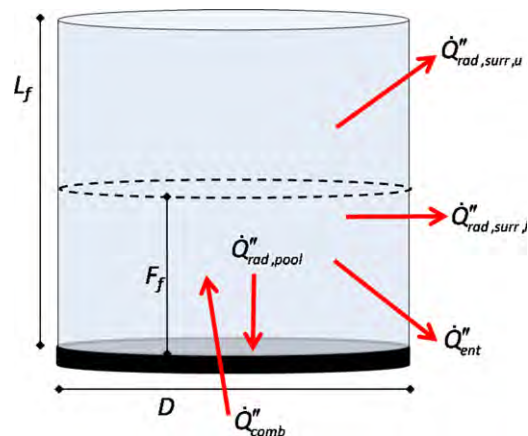


Fig. 2. Generalized schematic of pool fire showing steady-state energy balance including upper (u) and lower (l) radiative sections.

Since the diameter of the pan fire gives radiation-dominated heat transfer [10], all other processes (e.g., convection and conduction) were neglected.

The heat flux due to combustion is defined as

$$\dot{Q}_{comb}'' = \chi \dot{m}'' \Delta H_c \quad (2a)$$

where χ is the combustion efficiency of the system, \dot{m}'' is the fuel mass flux from the pan, and ΔH_c is the effective (lower) heat of combustion of the fuel. Empirical results from Mudan [12] show that for radiation-dominated pool fires, a maximum regression rate is correlated to $\dot{y}_{max} = 1.27 \times 10^{-6} \Delta H_c / \Delta H_{v, sen}$ where $\Delta H_{v, sen}$ is the sensible heat of vaporization or

$$\Delta H_{v, sen} = \Delta H_v + \int_{T_0}^{T_b} C_p dT \quad (2b)$$

where ΔH_v is the heat of vaporization at the boiling temperature T_b , C_p is the specific heat of the liquid fuel, and T_0 is the initial fuel temperature. Assuming that the actual regression rate is approximated to the maximum rate, the fuel mass flux can be determined by the regression rate multiplied by the fuel density or $\dot{m}'' = \rho \dot{y}$.

The radiation terms (surroundings and pool) of Eq. (1) are defined as

$$\dot{Q}_{rad}'' = \varepsilon F \sigma (T_f^4 - T_s^4) \quad (3a)$$

where σ is the Stefan–Boltzmann constant, T_f is the flame temperature above the pool, T_s is the surrounding temperature (T_b for radiation to the pool or ambient temperature for radiation to the surroundings), and ε is the emissivity as defined as $\varepsilon = 1 - e^{-\kappa \cdot d}$, where κ is the absorption–extinction coefficient of the flame and d is assumed to be either the diameter of the pool fire (D) for the radial direction or the flame fraction height ($L_f F_f$) for the lower section. F is the view factor or fraction of the total radiation directed to the surroundings or to the pool. F for the pool is determined from the view of the base of the cylinder radiating to the inside surface of the lower cylinder [11] multiplied by the flame fraction for the total cylinder or in mathematical terms:

$$F_{pool} = F_f (1 - 2H(\sqrt{1 + H^2} - H)) \quad (3b)$$

where H is defined as $L_f F_f / D$. L_f is correlated by Heskestad [13] as

$$L_f [m] = 0.235 (\dot{Q}_{comb}'' [kW/m^2] \cdot A_{pool})^{2/5} - 1.02D [m] \quad (3c)$$

where A_{pool} is the area of the pool. The view factor for the surroundings F_{surr} radiates to everything else or $1 - F_{pool}$.

The entrained air removes heat from the system by sensible heating of the introduced oxidizing (O_2) and inert (N_2) species. Assuming the hydrocarbon fuel converts only to H_2O and CO_2 , the amount of air entrained is stoichiometrically determined from the fuel flow rate \dot{m}'' and the combustion efficiency χ . The overall sensible heat removed from the system is determined by the integrated heat capacity for each species (i =fuel, O_2 , and N_2) multiplied by its flow rate or

$$\dot{Q}_{ent}'' = \sum_i \dot{m}_i'' \int_{T_0}^{T_f} C_{p,i} dT \quad (4)$$

Another contributor to the effectiveness of AFFF is how the foam spreads across the surface of the liquid fuel. The spreading factor (S) of a foam is the difference between the surface tension (σ) of the substrate (liquid fuel) and the added tensions of the foam and fuel/foam interface [2] or

$$S = \sigma_{sub} - (\sigma_{foam} + \sigma_{interface}) \quad (5)$$

This equation indicates that if the surface tension of the combustible liquid is greater than the combined forces from the foam and interface, the spreading factor is positive and the foam will spread over the surface of the liquid. Escobedo and Mansoori give an expression from which the surface tension of organic

compounds can be estimated for pure liquids [14] and for liquid mixtures [15]. The expression for pure liquids is

$$\sigma_{sub} = [P(\rho_l - \rho_v)]^4 \quad (6)$$

where ρ is the molar density in the liquid (l) and vapor (v) phases, and P is a temperature-independent compound-dependent parachor [16], which can be derived from statistical mechanics. Surface tension σ_{sub} for pure organic liquids typically ranges from 17 to 35 dyn/cm (mN/m) depending on species and temperature, while for water it ranges from 59 to 76 dyn/cm. Military-approved AFFF requires a minimum spreading factor of $S = 3$ dyn/cm over cyclohexane [2]. Surface tension of AFFF σ_{foam} is 16 dyn/cm, while the interfacial tension $\sigma_{interface}$ between AFFF foam and hydrocarbon liquids typically ranges between 1 to 6 dyn/cm [17]. Changes in the fuel composition and temperature could alter surface tension of the fuel or fuel/foam interface, thus altering the ability of AFFF to spread over the liquid pool.

5. Results and discussion

The average times including confidence intervals (95%) were determined and are shown in Figs. 3 and 4. Other pertinent data are also shown in Table 2 that includes the raw data for each test, the standard deviation, as well as t -test results (probabilities). Although not measured, the smoke from the JP-8 fires was qualitatively more prevalent than the other synthetic fuels. Fig. 1 shows side-by-side pool fires of SPK, SPK/JP-8 blend, and JP-8. These pool fires were not the actual mil-spec tests, but are representative of the smoke behavior observed in the mil-spec tests. The amount of aromatics in the JP-8 parent fuel may contribute to the amount of smoke.

When comparing the extinguishment times of the test fuels to JP-8, the probabilities ranged from 74.6% for the JP-8/S-8 fuel mixture to 26.7% for the S-2 diesel fuel. These probabilities were all greater than 5%, indicating no statistically significant difference in the t_{ex} . This indicates for these synthetic fuels that no significant difference was observed in the AFFF capabilities of extinguishing

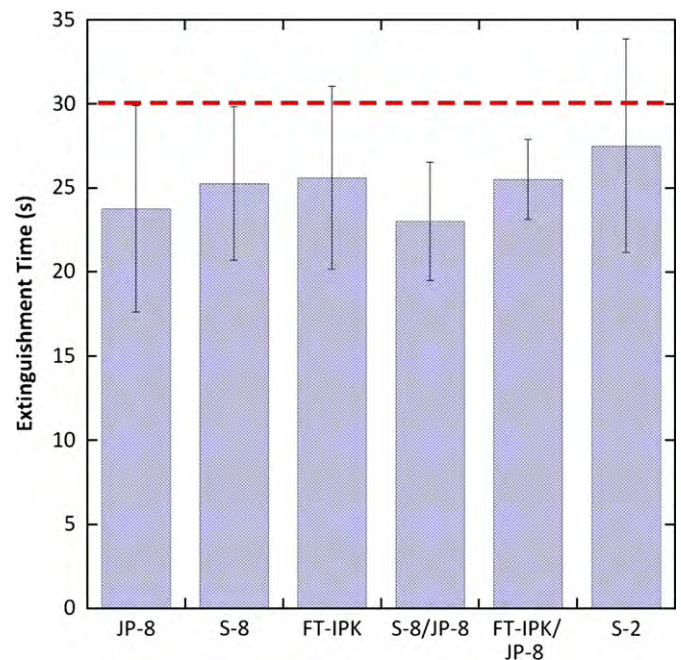


Fig. 3. Average extinguishment times for mil-spec experiments with corresponding 95% confidence intervals. The dashed lined indicates the mil-spec standard for extinguishment of 30 s with nearly all fuels below this standard.

the fire when compared to JP-8. In addition, values of t_{ex} (average value of measured t_{ex} plus upper limit of the 95% confidence interval) were below the desired mil-spec value of 30 s, except for the FT-IPK and S-2 fuels. This is shown graphically in Fig. 3 with 95% confidence intervals.

The burnback time probabilities ranged from 98.8% for the FT-IPK/JP-8 fuel mixture to 0.2% for the S-8/JP-8 fuel mixture. The FT-IPK/JP-8 mixture was the only burnback probability greater than 5%, having similar burnback behavior to that of JP-8. All other probabilities were less than 5%, indicating statistically that the burnback characteristics from JP-8 were not similar. The average t_{bb} values for all fuels (except FT-IPK/JP-8) were greater than the t_{bb} for JP-8, indicating that these fuels (S-8, FT-IPK, S-8/JP-8, and S-2) were better than JP-8 with regards to burnback safety. However, because of the limited number of tests performed on the S-2 fuels and the large 95% confidence intervals (see Table 2 and Fig. 4), this conclusion (probability) may change. Values of t_{bb} (averages value of measured t_{bb} minus lower limit of the 95% confidence interval) were above the desired mil-spec value of 360 s (shown in Fig. 4).

Physical properties of hexane (C_6H_{14}) and benzene (C_6H_6) were used for the energy balance model to represent aliphatic and aromatic fractions in the fuel composition. With one equation (Eq. (1)) and one unknown (T_f), the energy balance can be solved. Using the model development shown above, three variables (F_f , n [molar fraction of hexane], and χ) could alter the overall flame temperature (T_f) and the radiation to the pool ($\dot{Q}''_{rad,pool}$). Estimate baseline values were assigned for each variable ($F_f=0.25$, $n=0.9$, and

$\chi=0.9$). This baseline set gave reasonable percentages of total radiation ($\dot{Q}''_{rad,surr} + \dot{Q}''_{rad,pool} / \dot{Q}''_{comb}$) of 29.4% and radiation to the pool $\dot{Q}''_{rad,pool} / \dot{Q}''_{comb}$ of 1.4%, each similar to typically assumed values (30% and 2%, respectively) [18].

Since each variable ranges from 0 to 1, baseline values were maintained for two variables while changing the final variable to show how each variable could affect T_f or $\dot{Q}''_{rad,pool}$ (see Fig. 5). Model results show that by increasing combustion efficiency (χ), both T_f and $\dot{Q}''_{rad,pool}$ also increase. Similarly, as the amount of hexane increases in the fuel composition (n), both T_f and $\dot{Q}''_{rad,pool}$ increase linearly, though not as significant when compared with χ . As the flame fraction increases (F_f ; i.e., less soot production), T_f remains the same while $\dot{Q}''_{rad,pool}$ peaks at $F_f \approx 0.2$ and ranges from 15 to 45 kW/m².

Fig. 1 shows significant differences in the amount of smoke between JP-8 and SPK (S-8), with the approximate level where smoke obscures the pool fire for each fuel. Since the SPK fuels contain little to no aromatics (mostly aliphatic), pure hexane ($n=1$) was used to model its behavior with a F_f of 0.5, while jet fuel contains ~25% aromatics, a 3:1 mixture of hexane:benzene ($n=0.75$) was used with a F_f of 0.15. Flame temperatures for these cases showed pure hexane (2057 K) being slightly higher than the mixture (2024 K), a 1.7% increase. However, radiation to the pool showed pure hexane (32.5 kW/m²) being lower than the mixture (43.6 kW/m²), a 25% decrease. This decrease in radiant energy to the pool due mainly to limited soot obscuration (i.e., having a higher flame fraction) indicates that more energy could remain in the pool following extinguishment of AFFF with JP-8 rather than a synthetic fuel. This residual energy could destabilize the AFFF faster, thus allowing for increased burnback potential with JP-8, as seen in most experiments.

Using the method of Escobedo and Mansoori [14] to estimate surface tension, Eq. (6) was used for pure organic liquids of hexane, 2-methylpentane, benzene, and toluene at room temperature (293 K) up to the boiling temperature of each liquid. Values (all in dyn/cm) ranged from 18.6 to 13.1 ($T_b=341.9$ K) for hexane, from 18.3 to 13.6 ($T_b=333.4$ K) for 2-methylpentane, from 32.3 to 23.1 ($T_b=353.2$ K) for benzene, and from 32.7 to 20.2 ($T_b=383.8$ K) for toluene. All surface tension profiles decreased linearly with temperature. The surface tension using a binary mixture of hexane and benzene was also calculated [15] at the boiling temperature of the mixture. Results are shown in Fig. 6 with pure hexane having a surface tension 12.3 dyn/cm lower than pure benzene. Again comparing hexane and benzene to aliphatic and aromatic components of JP-8, the surface tension of a pure aliphatic fuel (i.e., SPK) would be 1.6 dyn/cm lower than 75% aliphatic fuel (i.e., JP-8). The aliphatic content in synthetic fuel should lower the surface tension of the fuel, making foam duration/spreading on the surface more difficult. However, experiments showed improved burnback times using synthetic fuels, indicating that surface tension due to composition (e.g., aliphatic content) is not the deciding factor for burnback safety.

The energy model predicted that for sooty flames, the energy transferred to the pool would increase, which would increase the temperature of the pool after extinction (assuming similar

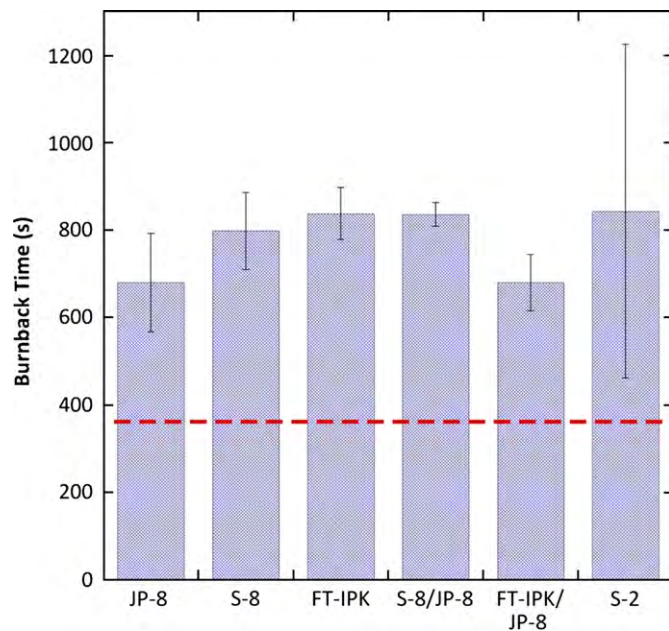


Fig. 4. Average burnback times for mil-spec experiments with corresponding 95% confidence intervals. The dashed lined indicates the mil-spec standard for burnback of 360 s with all fuels above this standard.

Table 2

Times of extinguishment and burnback including averages, standard deviations, and probabilities for the various fuel configurations.

Fuel	Raw t_{ex} (s)	$t_{ex} \pm \sigma_{ex}$ (s)	p_{ex} (%)	Raw t_{bb} (s)	$t_{bb} \pm \sigma_{bb}$ (s)	p_{bb} (%)
JP-8	26,21,20,28	23.8 ± 3.9	100.0	638,738,601,741	679.5 ± 70.9	100.0
S-8	27,26,21,27	25.3 ± 2.9	55.6	833,855,745,755	797.0 ± 55.2	4.0
FT-IPK	22,27,20,30,29	25.6 ± 4.4	53.0	842,811,858	837.0 ± 23.9	1.5
S-8/JP-8	18,24,24,24,25	23.0 ± 2.8	74.6	816,830,840,870,820	835.2 ± 21.6	0.2
FT-IPK/JP-8	29,26,24,23,24,27	25.5 ± 2.3	38.7	681,652,798,658,661,623	678.8 ± 61.3	98.8
S-2	28,27	27.5 ± 0.7	26.7	813,873	843.0 ± 42.4	4.4

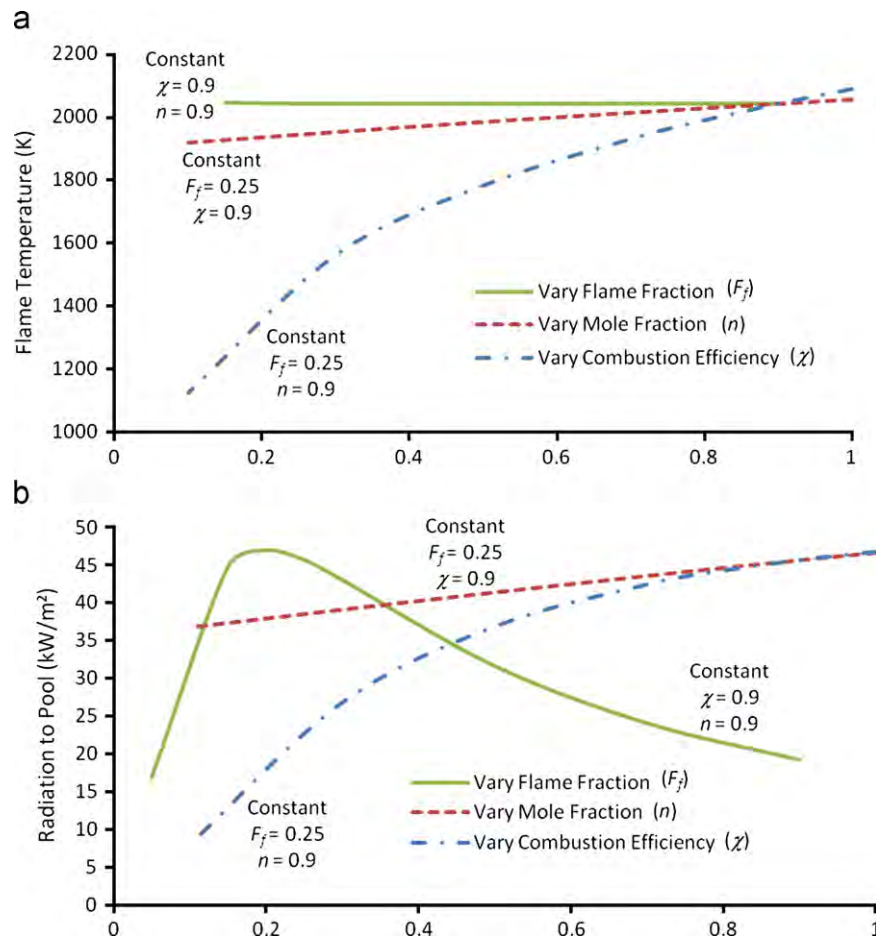


Fig. 5. (a) Temperature and (b) radiation to pool as flame fraction (F_f), hexane mole fraction (n), and combustion efficiency (χ) change.

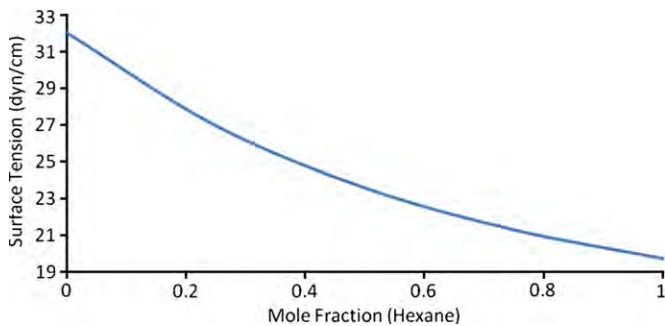


Fig. 6. Surface tension of a mixture of hexane and benzene following Escobedo and Mansoori [15].

combustion times), which would also decrease the surface tension of the fuel layer, causing disintegration of the foam. Since the interfacial tension $\sigma_{interface}$ between the fuel and foam typically varies substantially (1–6 dyn/cm [17]), this could be a significant factor in determining burnback safety performance. This needs to be an item of research interest for the future.

6. Conclusions

Fire extinguishment tests were performed on conventional and synthetic jet fuels following the military specification MIL-F-24385 F for aqueous film-forming foam. Time of extinguishment and

burnback were recorded and compared to the baseline case fuel of JP-8, the current fuel used by the U.S. Air Force. It was found that no significant difference was found for extinguishment time between the JP-8 and the other synthetic fuels or blends, specifically S-8, FT-IPK, S-2, and corresponding blends. A difference for burnback time was found between JP-8 and most synthetic fuels or blends (except for FT-IPK/JP-8), indicating a higher safety factor for the synthetic fuels. The main factor that may explain the enhanced safety for synthetic fuels would be the radiation from the sooty (JP-8) flames transferred to the fuel surface, which would also increase the fuel temperature, reducing the surface tension of the liquid fuel. The added heat and decreased surface tension would disintegrate and dissipate the foam more quickly.

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